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OrbFit Impact Solutions for Asteroids (99942) Apophis and (144898) 2004 VD17

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1. Introduction

The best systems with the exact impact solutions for dangerous asteroids are presented by the JPL Sentry System: http://neo.jpl.nasa.gov/risk/ and by the NEODyS CLOMON2: http://newton.dm.unipi.it/neodys/index.php?pc=4.1

From many years on the top of these lists were two asteroids: (99942) Apophis (is still up now, October 2011) and (144898) 2004 VD17 – now is removed from the list of the dangerous asteroids. Thanks to the courtesy of those who made free available OrbFit software and its source code at: http://adams.dm.unipi.it/~orbmaint/orbfit/

It is now possible to compute individually dates of possible impacts of selected dangerous asteroids or the energy of impact and others impact factors. In this respect we investigated the motion of these recently discovered minor planets: (99942) Apophis and (144898) 2004 VD17 - the most dangerous for the Earth, according to the Impact Risk Page of NASA: http://neo.jpl.nasa.gov/risk/.

To compute exact impact solutions of asteroids it is necessary to include some additional small effects on the asteroid's motion. The inluence of relativistic effects, the perturbing massive asteroids, the Yarkovsky/YORP effects, solar radiation pressure, different ephemeris of the Solar System were investigated. To compute gravitational forces perturbing the motion of (99942) Apophis and (144898) 2004 VD17 from different massive asteroids, the free software Solex from A. Vitagliano was used:
http://chemistry.unina.it/~alvitagl/solex/.

SOLEX computes positions of the Solar System bodies by a method which is entirely based on the numerical integration of the Newton equation of motions (Vitagliano, A. 1997). With the use of Solex it was possible to compute all close approaches between (99942) Apophis and (144898) 2004 VD17 with all nearly 140000 numbering asteroids. Similar work with (15) Eunomia using Solex was done by Vitagliano and Stoss (2006).

Selected orbit solutions for (99942) Apophis and (144898) 2004 VD17 were presented during Meeting on Asteroids and Comets in Europe - May 12-14, 2006 in Vienna, Austria. At that time the new version of OrbFit (3.3.2) was released and gave better results of computations of impact probability mainly with the use of non linear monitoring and multi ple solutions method (Milani et al., 2002, Milani et al., 2005a and Milani et al., 2005b). The main goal of our work was to compare our results generated by OrbFit with the results presented by CLOMON2 system which uses the same OrbFit software and with the results of JPL NASA SENTRY. The second purpose was to prove how differently small effects in motion of asteroid change impact solutions. It was possible thanks to public available source code of the OrbFit software. The orbital uncertainty of an asteroid is viewed as a cloud of possible orbits centered on the nominal solution, where density is greatest. This is represented by the multivariate Gaussian probability density and the use of this probability density relies on the assumption that the observational errors are Gaussian (Milani et al., 2002). Now, August 2011, we have new version of the OrbFit software, v.4.2, implementing the new error model based upon Chesley, Baer and Monet (2010).

2. Some impact solutions for (99942) apophis

2.1 The Influence of *sigma_LOV* and radar observation

The orbital elements of (99942) Apophis in Tab. 1 were computed by the author using all 1007 observations up to this date (Sep. 14th, 2006) and software OrbFit where M - mean anomaly, a - semimajor axis, e - eccentricity, ω_{2000} – argument of perihelion, Ω_{2000} - longitude of the ascending node, i_{2000} - inclination of the orbit. These orbital elements are referred to the *J2000* equator and equinox.

$M[deg]$	$a[AU]$	e	$\omega_{2000}[deg]$	$\Omega_{2000}[deg]$	$i_{2000}[deg]$
333.507245	0.92226793	0.19105946	126.393030	204.460151	3.331317

Table 1. (99942) Apophis: orbital elements. 1007 observations from 885 days (2004/03/15.11 - 2006/08/16.63), *rms*=0.302". Nominal orbit: epoch 2006 Jun. 14.0.

Fig. 1 presents the orbit of (99942) Apophis projected to the ecliptic plane, where x-axis is directed to vernal equinox. The dotted lines indicate the part of the orbit below the ecliptic plane. It is clearly seen that orbit of this asteroid crosses the orbit of the Earth and approaches that of Venus. The influence of the radar observations in computations of impact solutions for (99942) Apophis were performed using all observations available before date of MACE 2006. There were 987 optical observations (of which 6 were rejected as outliers) from 2004/03/15.108 to 2006/03/26.509, and also seven radar data points on 2005/01/27, 2005/01/29, 2005/01/31 and 2005/08/07.

Tab. 2 lists impact solutions for (99942) Apophis computed by the author for these settings: multiple solutions, use scaling, line of variation (LOV) with the largest eigenvalue (Milani et al. 2002) in comparison with these published at NEODYS CLOMON2
site: http://newton.dm.unipi.it/neodys/index.php?pc=1.1.2&n=99942
and at the NASA SENTRY site: http://neo.jpl.nasa.gov/risk/a99942.html.

The software OrbFit ver. 3.3.1 for UNIX was used. In this impact table everywhere weighing of observations was as CLOMON2. In Tab. 2 *date* is a calendar day for the potential impact; *dist.[RE]* – minimum distance, the lateral distance from LOV (line of variation, which represent the central axis of the asteroid's elongated uncertainty region); *impact probability* - computed with a Gaussian bidimensional probability density; *IW* –

computed solutions by author of this paper; *nr* denotes solution without radar observations and σ equal to *sigma_LOV* - approximate location along the LOV in sigma space; values of sigma are usually in the interval [-3,3] which represent 99.7 % probability of occurrence of real asteroid in this confidence region (Milani et al. 2002). The impact probability is not reported if the computed value is less than 1E-11. The presented σ are only the input data in OrbFit software, not the real σ - positive or negative, along the LOV. For example $\sigma = 3$ denotes that the real σ is between -3 and +3. For different setting of σ value we observe slightly different impact solutions mainly in the date of possible impact. The differences between the results from the NEODyS (CLOMON2) and the JPL NASA (SENTRY) are evident because they are independent systems as state at: http://neo.jpl.nasa.gov/risk/doc/sentry_faq.html. For example impact probabilities different by a factor of ten or so are not extraordinary.

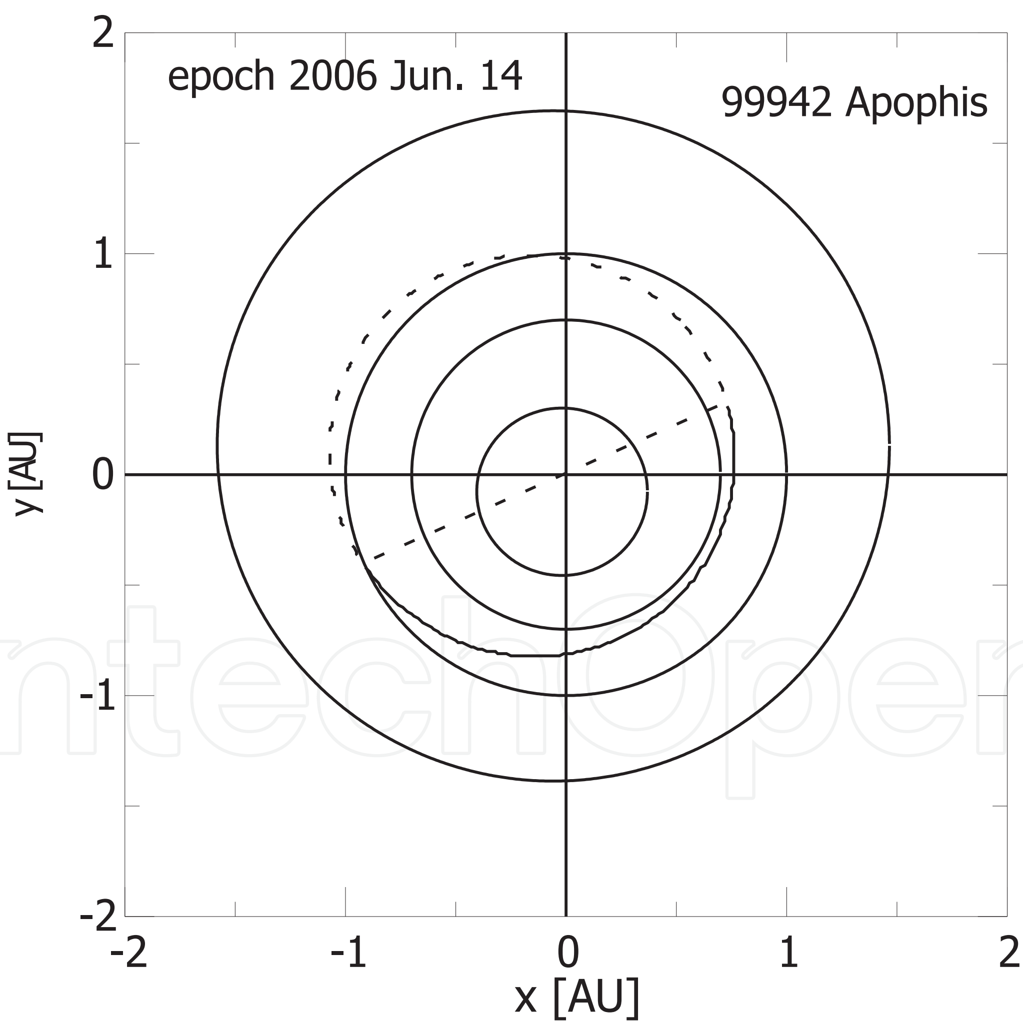

Fig. 1. The orbit of (99942) Apophis projected to the ecliptic plane, where *x*-axis is directed to vernal equinox.

date	dist[RE]	impact probability	source
2035/04/14.131	1.36	1.82E-05	IW, 3 σ, nr
2036/04/13.371	1.15	1.61E-04	CLOMON2
2036/04/13.370	0.53	1.60E-04	SENTRY
2036/04/13.371	1.14	3.46E-05	IW, 3 σ
2036/04/13.371	1.15	1.02E-04	IW, 3 σ, nr
2036/04/13.371	1.14	3.46E-05	IW, 6 σ,
2037/04/13.644	1.36	1.96E-07	CLOMON2
2037/04/13.640	0.63	2.00E-07	SENTRY
2037/04/13.644	1.36	2.46E-05	IW, 3 σ, nr
2037/04/13.644	1.36	1.45E-08	IW, 6 σ
2038/04/13.659	1.73	1.59E-10	CLOMON2
2040/04/13.135	1.65	8.17E-09	IW, 3 σ
2040/04/13.173	1.11	3.40E-08	IW, 3 σ, nr
2042/04/13.726	1.80	3.62E-07	CLOMON2
2042/04/13.710	0.99	4.60E-07	SENTRY
2042/04/13.719	1.38	9.29E-08	IW, 3 σ
2044/04/13.297	2.10	2.57E-07	CLOMON2
2044/04/13.296	2.08	5.89E-08	IW, 3 σ
2044/04/13.264	1.79	6.23E-11	IW, 6 σ
2046/04/13.797	1.98	3.84E-08	IW, 3 σ, nr
2053/04/12.913	1.39	1.80E-07	IW, 3 σ
2054/04/13.401	1.46	6.95E-09	CLOMON2
2054/04/13.400	0.60	7.20E-09	SENTRY
2054/04/13.403	1.27	1.14E-06	IW, 3 σ, nr
2054/04/13.404	1.30	4.79E-10	IW, 6 σ
2055/04/13.730	1.25	4.33E-07	IW, 3 σ, nr
2056/04/12.867	0.70	3.71E-08	IW, 3 σ, nr
2059/04/13.954	2.08	4.31E-10	CLOMON2
2059/04/13.954	2.07	4.81E-08	IW, 3 σ, nr
2059/04/13.953	2.07	3.48E-11	IW, 6 σ
2063/04/13.796	1.30	1.80E-10	CLOMON2
2063/04/13.795	1.26	1.18E-11	IW, 6 σ
2068/04/12.631	0.69	1.77E-06	IW, 3 σ
2068/04/12.631	0.26	1.04E-06	IW, 6 σ
2069/04/13.078	0.97	2.58E-07	CLOMON2
2069/04/13.078	0.99	2.46E-07	IW, 3 σ
2069/10/15.972	0.48	1.20E-07	CLOMON2
2069/10/15.970	0.41	2.55E-07	IW, 3 σ
2069/10/15.970	0.27	2.32E-07	IW, 6 σ
2078/04/13.442	1.93	5.23E-09	CLOMON2

Table 2. (99942) Apophis: influence of different *sigma_LOV* and radar observations for computed impact solutions. Note nr means solution without radar observations. SENTRY and CLOMON2 are systems of impact risk computing of the JPL NASA and the NEODYS, respectively. IW are results by the author.

From results in Tab. 2 we can see that we must include radar observations in computations of impact solutions for (99942) Apophis. Without radar observations we have not impact solutions in 2042, 2044, 2053 and beyond 2063 year. Instead we have mistaken dates of possible impacts in 2035, 2046, 2055 and 2056 years. The usefulness of radar observations is presented e.g. in the paper of Yeomans et. al. (1987). No impact solutions for σ=1 were found. Time of computations of single solution was about 3 hrs with 1.7 MHz processor.

2.2 (99942) Apophis: Approaching asteroids

To compute exactly impact solutions for (99942) Apophis it is necessary to include gravitational perturbations of approaching massive asteroids. Usually SENTRY include 3 massive asteroids: (1) Ceres, (2) Pallas and (4) Vesta, CLOMMON2 - as SENTRY or 4 asteroids: (1) Ceres, (2) Pallas, (4) Vesta and (10) Hygiea. Using the software Solex ver. 9.0 we have investigated all close approaches of about 140,000 numbered asteroids known in Sept. 2006 with (99942) Apophis within 0.2 AU till 2100 year. We have found 4 asteroids with several close approaches to (99942) Apophis: (433) Eros, (887) Alinda, (1685) Toro and (1866) Sisyphus. These selected asteroids together with the 4 massive ones (Ceres, Pallas, Vesta and Hygiea) were included to equations of motion of (99942) Apophis. The computations of influence of gravitational perturbations of these asteroids for the motion of (99942) Apophis were performed using software OrbFit ver. 3.3.1. The masses of asteroids were taken from Michalak (2001) and from Solex as computed by A. Vitagliano. First of all we must include Ceres in our gravitational model which has about 30 % of the mass of the main belt asteroids and the asteroids which have the closest approaches with (99942) Apophis. All results in Tab. 3 are computed using the JPL Planetary and Lunar Ephemerides DE405 and relativistic effects.

The suitable results in Tab. 3 were computed based on 996 optical observations of which 5 are rejected as outliers from 2004/03/15.108 to 2006/07/27.614, and also on seven radar data points on 2005/01/27, 2005/01/29, 2005/01/31, 2005/08/07 and 2006/05/06.

In Tab. 3 and in all others SENTRY denotes the results from the JPL NASA and CLOMON2 from the NEODYS site. The author results are: *IW-a*: no perturbing asteroids; *IW-b*: Ceres and 4 close approaching asteroids to (99942) Apophis: Eros, Alinda, Toro, Sisyphus; *IW-c*: 4 perturbing asteroids: Ceres, Pallas, Vesta, Hygiea; *IW-d*: 5 perturbing asteroids: Ceres, Pallas, Vesta, Hygiea and approaching asteroid Eros; *IW-e*: 3 perturbing asteroids: Ceres, Pallas and Vesta.

From Table 3 we can see that there is significant role of massive asteroids in motion of Apophis, specially after 2042. Some impact solutions does not exist in given year. For example, in April, 2069 there are only impact solutions with additional perturbing effect from together: Ceres, Eros, Alinda, Toro, Sisyphus and the second solution with perturbations from Ceres, Pallas, Vesta and Hygiea.

Fig. 2 shows the changes of differences in mean anomaly between asteroid (99942) Apophis on nominal orbits for different cases. In Fig. 2(a) there are differences in mean anomaly between (99942) Apophis with and no relativistic effects included. Fig. 2(b) presents differences in mean anomaly of (99942) Apophis between orbits computed without perturbing asteroids and with perturbation from: *1* - Ceres, Pallas and Vesta, *2* - Ceres, Pallas, Vesta, and Hygiea and *3* - Ceres, Pallas, Vesta, Hygiea and Eros. It is clear from Fig.

2(a) that a relativistic effects play a great role in motion of asteroid - over 30 degs difference in mean anomaly between asteroids with and no these effects in the next 100 years. However in Fig. 2(b) the infuence of close approaching asteroids is evident but these effects are several times smaller than the relativistic effects. The rapidly changes in differences in mean anomaly in Fig. 2 are connected with the close approaches of (99942) Apophis with the Earth in the years: 2029 (0.00025 *AU*) and 2057 (0.022 *AU*) for the nominal orbits. Hence chaoticity of the motion of the asteroid appears (Wlodarczyk, 2001). The infuence of number of perturbing asteroids on impact solutions for (99942) Apophis lists Tab. 3.

date	dist[RE]	impact probability	source
2036/04/13.370	0.53	2.20E-05	SENTRY
2036/04/13.371	1.15	2.40E-04	CLOMON2
2036/04/13.371	1.15	2.40E-04	IW-a
2036/04/13.371	1.15	2.12E-05	IW-b
2036/04/13.371	1.15	2.39E-04	IW-c
2036/04/13.371	1.15	2.12E-05	IW-d
2036/04/13.371	1.15	2.39E-05	IW-e
2037/04/13.640	0.63	8.5E-08	SENTRY
2042/04/13.715	2.06	6.59E-08	CLOMON2
2042/04/13.718	1.37	6.61E-08	IW-a
2042/04/13.717	1.40	6.09E-08	IW-b
2042/04/13.717	1.38	6.73E-08	IW-c
2042/04/13.717	1.40	6.11E-08	IW-d
2042/04/13.717	1.38	6.73E-08	IW-b
2044/04/13.296	2.09	4.07E-08	CLOMON2
2044/04/13.298	2.13	3.89E-08	IW-a
2044/04/13.294	2.11	3.70E-08	IW-b
2044/04/13.298	2.13	3.45E-08	IW-d
2053/04/12.913	1.39	1.27E-07	CLOMON2
2054/04/13.400	0.59	2.70E-09	SENTRY
2068/04/12.630	0.62	1.79E-06	IW-a
2068/04/12.630	0.52	1.63E-06	IW-c
2068/04/12.633	0.48	8.19E-07	IW-d
2068/04/12.631	0.37	1.03E-06	IW-e
2069/04/13.079	2.00	4.43E-07	CLOMON2
2069/04/13.078	0.97	5.51E-07	IW-b
2069/04/13.079	0.96	4.72E-07	IW-c
2069/10/15.596	0.62	1.02E-07	CLOMON2
2069/10/15.972	0.49	2.63E-07	CLOMON2
2069/10/15.970	0.38	4.70E-07	IW-b
2069/10/15.972	0.59	2.90E-07	IW-c
2069/10/15.971	0.56	4.21E-07	IW-d
2077/04/13.166	1.79	4.33E-08	CLOMON2

Table 3. (99942) Apophis: influence of approaching asteroids for computed impact solutions.

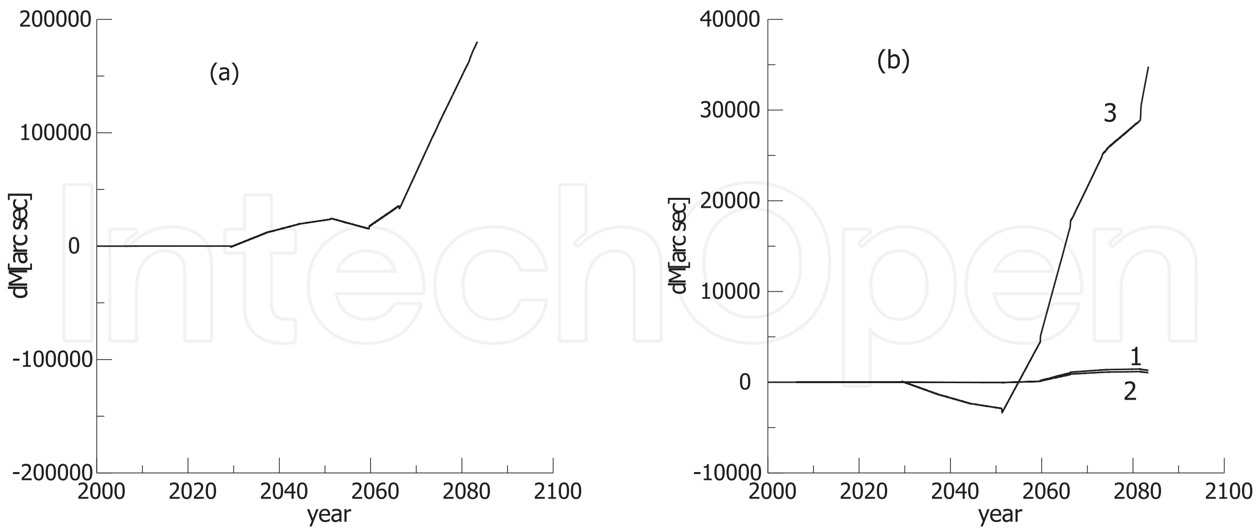

Fig. 2. (99942) Apophis. Differences in mean anomaly between nominal orbits from different solutions: *(a)* - 4 perturbing asteroids: relativistic/non relativistic effects included; *(b)* - different number of perturbing asteroids (see text).

2.3 (99942) Apophis: The JPL Ephemerides

The question was appeared how the model of the Solar System used influences for the impact solutions of (99942) Apophis. Generally the JPL Planetary and Lunar Ephemerides DE203, DE405 or DE406 (SENTRY), DE405 (CLOMON2), DE406 (some in this paper) or DE405/WAW (Sitarski, 2002) were used. DE405 ephemerides (includes both nutations and librations) are computed for time span JED 2305424.50 (1599 DEC 09) to JED 2525008.50 (2201 FEB 20). DE406 is the new "JPL Long Ephemeris" (includes neither nutations nor librations). They works for time span JED 0624976.50 (-3001 FEB 04) to 2816912.50 (+3000 MAY 06). This is the same ephemeris as DE405, though the accuracy of the interpolating polynomials has been lessened. Using OrbFit software v.3.3.2 for Linux and 994 optical observations of (99942) Apophis from 2004/03/15.108 to 2006/06/02.602, and also on seven radar data points on 2005/01/27, 2005/01/29, 2005/01/31, 2005/08/07 and 2006/05/06 we have found some impact results for different planetary ephemerides.

Date	Dist. [RE]	Author	JPL
2036/04/13.371	1.15	CLOMON2	(DE405)
2036/04/13.371	1.15	IW	DE405
2036/04/13.371	1.15	IW	DE406
2042/04/13.720	1.41	CLOMON2	(DE405)
2042/04/13.718	1.37	IW	DE405
2042/04/13.718	1.37	IW	DE406
2044/04/13.295	2.09	CLOMON2	(DE405)
2044/04/13.295	2.08	IW	DE405
2044/04/13.295	2.05	IW	DE406

Table 4. (99942) Apophis: Influence of the JPL Ephemerides on impact solutions.

As we can see in Tab. 4 the results for the JPL ephemerides DE405 and DE406 are almost the same. However Andrea Milani in his e-mail on Juni, 6-th, 2006 wrote: "A particularly good result (using DE405 or DE406), given the strong instability of these solutions, as a result of the very close approach in 2029. My congratulations for your very accurate computations."

3. Some impact solutions for (144898) 2004 VD17

3.1 The influence of *sigma_LOV* and weighting

The orbital elements of (144898) 2004 VD17 presented in Tab. 5 were computed using all known observations up to 14th Sept., 2006 by the author with the software OrbFit 3.3.2 for Linux where M - mean anomaly, a - semimajor axis, e - eccentricity, ω_{2000} - argument of perihelion, Ω_{2000} - longitude of the ascending node, i_{2000} - inclination of the orbit. These orbital elements are referred to the *J2000* equator and equinox. Fig. 3 presents the orbit of (144898) 2004 VD17 projected to the ecliptic plane, where x-axis is directed to vernal equinox. The dotted lines indicate the part of the orbit below the ecliptic plane. The orbit of this asteroid crosses the orbit of the Earth and that of Venus.

$M[deg]$	$a[AU]$	e	$\omega_{2000}[deg]$	$\Omega_{2000}[deg]$	$i_{2000}[deg]$
340.212924	1.5082009	0.58866739	90.686443	224.242137	4.223018

Table 5. (144898) 2004 VD17: orbital elements. 933 observations from 1553 days (2002/02/16.46 - 2006/05/24.10), *rms*=0.351". Nominal orbit: epoch 2006 Jun. 14.0.

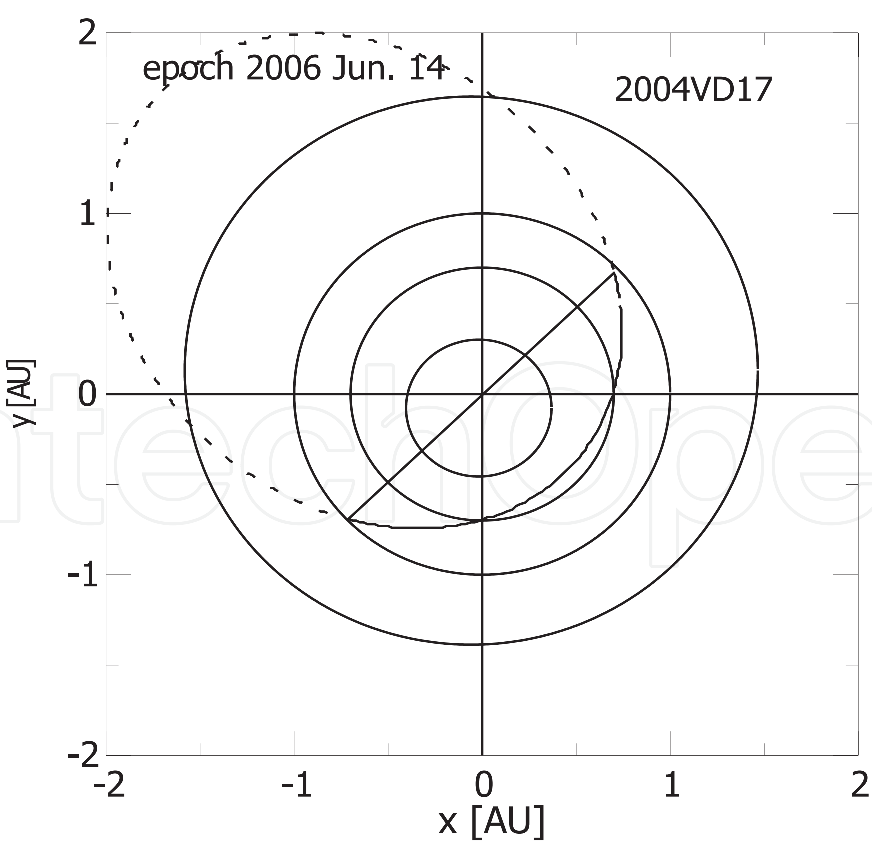

Fig. 3. The orbit of (144898) 2004 VD17 projected to the ecliptic plane, where x-axis is directed to vernal equinox.

The impact solutions of (144898) 2004 VD17 in Tab. 6 were computed using 891 optical observations (of which 1 was rejected as outlier) from 2002/02/16.462 to 2006/04/22.871. These observations were available up to date of MACE 2006.

Tab. 6 shows that the infuence of σ and weighting of observations has a small influence for impact solutions for (144898) 2004 VD17.

Date	Dist. [RE]	Impact probability	Source
2102/05/04.894	0.51	6.66E-4	CLOMON2
2102/05/04.894	0.44	6.7 E-4	SENTRY
-	-		IW, 1 σ
2102/05/04.894	0.52	6.71E-4	IW, 1.5 σ
2102/05/04.894	0.52	6.22E-4	IW, 1.5 σ ,w=1
2102/05/04.894	0.52	6.71E-4	IW, 2 σ
2102/05/04.894	0.52	6.71E-4	IW, 2 σ, w=1
2102/05/04.894	0.52	6.66E-4	IW, 3 σ
2102/05/04.894	0.52	6.22E-4	IW, 3 σ, w=1
2102/05/04.894	0.52	6.30E-4	IW, 3 σ, no scal.
2102/05/04.894	0.52	9.37E-4	IW, 3 σ, fn
2102/05/04.894	0.52	6.71E-4	IW, 4 σ
2102/05/04.894	0.52	6.71E-4	IW, 5 σ
2102/05/04.894	0.52	6.71E-4	IW, 6 σ
2104/05/04.373	0.58	3.26E-7	CLOMON2
-	-		SENTRY
-	-		IW, 1 σ
2104/05/04.372	1.05	3.29E-7	IW, 1.5 σ
2104/05/04.377	1.15	3.14E-7	IW, 1.5 σ ,w=1
2104/05/04.374	0.54	3.29E-7	IW, 2 σ
2104/05/04.374	0.54	3.29E-7	IW, 2 σ, w=1
2104/05/04.373	0.74	3.29E-7	IW, 3 σ
2104/05/04.374	0.52	3.10E-7	IW, 3 σ, w=1
2104/05/04.374	0.55	3.15E-7	IW, 3 σ, no scal.
2104/05/04.375	0.58	4.80E-7	IW, 3 σ, fn
2104/05/04.374	0.52	3.31E-7	IW, 4 σ
2104/05/04.376	0.88	3.38E-7	IW, 5 σ
2104/05/04.374	0.54	3.36E-7	IW, 6 σ
2105/05/04.655	0.41	3.84E-8	IW, 3 σ, no scal.
2109/05/04.637	0.62	9.72E-9	IW, 1.5 σ, w=1

Table 6. (144898) 2004 VD17: Inluence of different *sigma_LOV* (σ) and weighting for impact solutions.

Mainly it have an effect on value of impact probability. Similar the problem of scaling of LOV (Milani et al., 2002) is neglecting in this case. Otherwise everywhere weighing is as CLOMON2, further settings are: multiple solution, use scaling (fn denotes impact solution without scaling), LOV with the largest eigenvalue; *w*=1 denotes without weighing of observations. On the MPML (Minor Planet Mailing List) forum the problem was connected with 4 first observations of (144898) 2004 VD17 recovered from 2002 year. It was appear that adding these observations does not affect on impact solutions considerably. In Tab. 6 *fn* denotes impact solutions without first four observations from 2002.

3.2 (144898) 2004 VD17: Approaching asteroids

As for (99942) Apophis, to compute exactly impact solutions for (144898) 2004 VD17 it is necessary to include gravitational perturbations of approaching asteroids. Using software Solex90 we have computed all close approaches of about 140,000 numbering asteroids known in Sept. 2006 with (144898) 2004 VD17 till 2110 year. We have found 5 asteroids with several close approaches to (144898) 2004 VD17 : (3) Juno, (6) Hebe, (7) Iris, (18) Melpomene and (51) Nemausa. These selected asteroids with the 4 massive ones were included to equations of motion of (144898) 2004 VD17 .

The computations of infuence of gravitational perturbations of these asteroids for the motion of (144898) 2004 VD17 were performed using software OrbFit 3.3.1. The masses of asteroids were taken from Michalak (2001) and from Solex90 as computed by A. Vitagliano (2006). The computations were based on 902 optical observations (of which 3 are rejected as outliers) from 2002/02/16.462 to 2006/04/29.090.

Date	Dist. [RE]	Impact probability	Source
2102/05/04.894	0.51	5.58 E-04	CLOMON2
2102/05/04.894	0.52	5.53 E-04	IW-a
2102/05/04.894	0.52	5.61 E-04	IW-d
2102/05/04.894	0.52	5.54 E-04	IW-b
2102/05/04.893	0.53	6.37 E-04	IW-bnrel
2102/05/04.894	0.52	5.59 E-04	IW-c
2102/05/04.894	0.52	5.53 E-04	IW-f
2102/05/04.890	0.44	7.35 E-04	SENTRY
2103/05/05.130	0.96	1.48 E-08	CLOMON2
2103/05/05.132	0.74	1.52 E-08	IW-b
2104/05/04.376	0.91	2.77 E-07	CLOMON2
2104/05/04.374	0.53	2.77 E-07	IW-a
2104/05/04.374	0.53	2.76 E-07	IW-d
2104/05/04.372	1.08	2.68 E-07	IW-b
2104/05/04.373	0.61	3.08 E-07	IW-bnrel
2104/05/04.376	0.87	2.78 E-07	IW-c
2104/05/04.377	1.09	2.74 E-07	IW-f
2109/05/04.515	0.84	7.60 E-09	IW-f

Table 7. (144898) 2004 VD17: Influence of approaching asteroids on impact solutions.

The results are in Tab. 7 where:
IW-a: solutions with 3. perturbing asteroids: Ceres, Pallas and Vesta
IW-b: 4 perturbing asteroids: Ceres, Pallas, Vesta, Hygiea
IW-bnrel: as *IW-b* without relativistic effects included
IW-c: 5 close approaching asteroids to (144898) 2004 VD17 : Juno, Hebe, Iris, Melpomene and Nemausa
IW-d: no perturbing asteroids
IW-f: all 9 perturbing asteroids: Ceres, Pallas, Juno, Vesta, Hebe, Iris, Hygiea, Melpomene and Nemausa

All results in Tab. 7 are computed with DE405 ephemeris and using relativistic effects (without case *IW-bnrel*). We can see that the impact solutions for asteroid (144898) 2004 VD17 does not differ so much using different number of perturbing asteroids as in the case of (99942) Apophis.

Fig. 4 shows the changes of differences in mean anomaly between asteroid (144898) 2004 VD17 on nominal orbits for different cases. In Fig. 4 (a) there are differences in mean anomaly between (144898) 2004 VD17 with and no relativistic effects included. Fig. 4 (b) presents differences in mean anomaly of (144898) 2004 VD17 between orbits without perturbing asteroids (solution *IW-d*) and with ones: 1 - solution *IW-a* (Ceres, Pallas and Vesta included), 2 - *IW-b* (Ceres, Pallas, Vesta, Hygiea), 3 - *IW-c* (Juno, Hebe, Iris, Melpomene, Nemausa), 4 - *IW-f* (Ceres, Pallas, Juno, Vesta, Hebe, Iris, Hygiea, Melpomene, Nemausa). The curves 1, 2 and 4 on the Fig. 4 are very similar, then the most perturbing effect comes from Ceres, Pallas and Vesta.

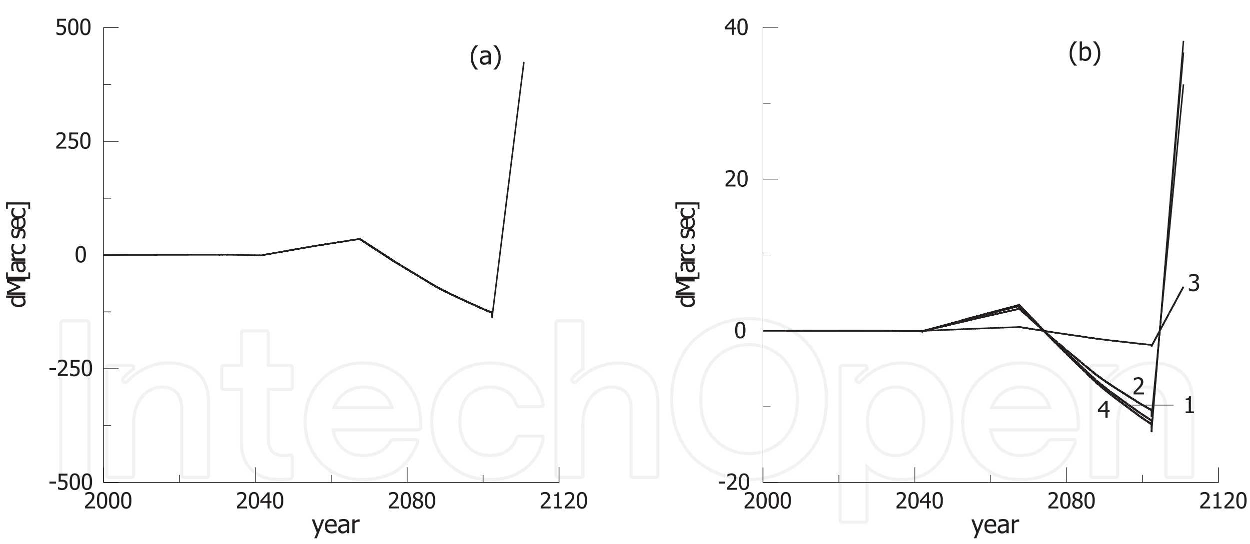

Fig. 4. (144898) 2004 VD17. Differences in mean anomaly between nominal orbit from different solutions: (a) – 4 perturbing asteroids: relativistic/non relativistic effects included; (b) – different number of perturbing asteroids: 1 - Ceres, Pallas and Vesta; 2 – Ceres, Pallas, Vesta and Hygiea; 3 – Juno, Hebe, Iris, Melpomene and Nemausa; 4 – Ceres, Pallas, Juno, Vesta, Hebe, Iris, Hygiea, Melpomene and Nemausa (see text) .

As in the case of (99942) Apophis the greatest infuence for motion (144898) 2004 VD17 have relativistic effects, about 10 times greater than the perturbing effects of additional massive asteroids. Even so we must use perturbing massive asteroids for computed precise impact solutions as Tab. 7 states. The rapidly changes in differences in mean anomaly in Fig. 4 are connected with the close approaches of (144898) 2004 VD17 with the Earth in the years: 2041 (0.01 AU), 2067 (0.03 AU) and 2102 (0.03 AU) for the nominal orbits. Hence chaoticity of the motion of the asteroid appears similar to this of (99942) Apophis but in the case of (144898) 2004 VD17 motion is less influenced.

3.3 (144898) 2004 VD17: The JPL Ephemerides

As in the case of (99942) Apophis using JPL Ephemerides DE405 and DE406 does not affect on the computed impact solutions in this short about 100 years time span.

4. Some new impact solution for (99942) Apophis and (144898) 2004 VD17

The new versions of the NEODyS-2: http://newton.dm.unipi.it/neodys/index.php?pc=0

and the new version of the OrbFit software: http://adams.dm.unipi.it/~orbmaint/orbfit/ were appeared.

Both they are based on the new error model (Chesley, Baer and Monet, 2010). The orbits are computed using star catalog debiasing and an error model with assumed astrometric errors RMS deduced from the tests of the paper cited above.

Also additional observations of (99942) Apophis and (144898) 2004 VD17 were added.

4.1 (99942) Apophis

Table 8 lists orbital elements of (99942) Apophis performed using all observations available to 1st Oct., 2011. There were 1481 optical observations (of which 8 were rejected as outliers), and also seven radar data points on 2005/01/27, 2005/01/29, 2005/01/31 and 2005/08/07. The orbit was computed by the author using the OrbFit software v. 4.2. The JPL NASA Ephemerides DE405 and additional perturbations from massive asteroids: (1) Ceres, (2) Pallas, (3) Juno, (4) Vesta and (10) Hygiea were used.

M[deg]	*a[AU]*	*e*	ω_{2000} *[deg]*	Ω_{2000}*[deg]*	i_{2000}*[deg]*
287.582224	0.9223003	0.19107616	126.42451	204.430372	3.331956
4.82E-05	1.13E-08	5.11E-08	7.57E-05	7.61E-05	1.63E-06

Table 8. (99942) Apophis: orbital elements together with theirs 1-σ variations. 1488 observations from 2555 days (2004/03/15.10789 – 2011/03/14.12528), *rms*=0.389". Nominal orbit: epoch 2011 Aug. 27.0.

Actually, both the Yarkovsky/YORP effect, which are part of a set of other astrodynamical effects that were taken summary only into account to prepare the present analysis, but that seems to be of significant influence in the orbital evolution of such objects. The preliminary results are in Table 9. The Yarkovsky and YORP (Yarkovsky-O' Keefe-Radzievskii-Paddack) effects are thermal radiation forces and torques that cause a drift of semimajor axes (computed value of **da/dt** in present work) of small asteroids and meteoroids and a change their spin vectors (obliquities). Because the Yarkovsky force depends on the obliquity, we can expect a complicated interplay between the Yarkovsky and YORP effects . Therefore it is difficult to estimate the influence of the Yarkovsky and YORP effects on the motion of asteroids separately. The result of the Yarkovsky effect is removal of small asteroids from the main belt to chaotic mean motion and secular apsidal or nodal resonance zones. Then they can be gradually transported to Earth-crossing orbits. Therefore the Yarkovsky and YORP effects are now considered in relation to objects crossing the Earth orbit, particularly they are important in the motion of potentially dangerous asteroids for the Earth.

The NEODyS presents only impact solutions based on 1399 optical observations (of which 5 are rejected as outliers) from 2004/03/15.127 to 2008/01/09.666 and also on seven radar data points on 2005/01/27, 2005/01/29, 2005/01/31, 2005/08/07 and 2006/05/06. The NEODyS lists possible impact in 2036, 2056, 2068 – two solutions, 2076 and in 2103. Their solutions are based on Monte Carlo method, including a probabilistic model of the Yarkovsky effect. In this way impact solutions are model dependent. Without any non-gravitational perturbation model they found possible impact in 2068/04/12.632 with the probability of about 3.81 10^{-6}. Similar impact solutions are from the JPL NASA.

Using all 1490 observations of Apophis and the OrbFit software I computed value of the semimajor axis drift of Apophis equal to **da/dt**=+180 10^{-4} AU/Myr connected with the Yarkovsky/YORP effects and got following impact solutions as are presented in Table 9. Additional perturbations from (1) Ceres, (2) Pallas and (4) Vesta are included.

Date	Dist. [RE]	Impact probability
2043/04/13.901	2.01	2.08 E-07
2064/04/12.824	1.52	1.44 E-06

Table 9. (99942) Apophis. Impact solutions with the Earth using semimajor axis drif, **da/dt**= =+180 10^{-4} AU/Myr, computed by the author. Similar value of **da/dt**= (235+/-50) 10^{-4} AU/Myr has computed Grzegorz Sitarski (private information).

To compute impact solutions of Apophis we must know exact uncertainty from the Yarkovsky effects and physical parameter uncertainties of Apophis together with the astrometric biases and radiation pressure (Giorgini et al. 2007).

4.2 (144898) 2004 VD17

Table 10 lists orbital elements of (144898) 2004 VD17 performed using all observations available up to 1st Oct., 2011. There were 981 optical observations of which 4 were rejected as outliers. The orbit was computed by the author using the OrbFit software v. 4.2. The JPL NASA Ephemerides DE405 and additional perturbations from massive asteroids: (1) Ceres, (2) Pallas, (3) Juno, (4) Vesta and (10) Hygiea were used.

$M[deg]$	$a[AU]$	e	$\omega_{2000}[deg]$	$\Omega_{2000}[deg]$	$i_{2000}[deg]$
271.359237	1.5081219	0.58860168	90.762748	224.187119	4.223233
9.96E-05	7.36E-08	4.86E-08	3.52E-05	7.93E-06	7.93E-06

Table 10. (144898) 2004 VD17: orbital elements together with theirs 1-σ variations. 981 observations from 2513 days (2002/02/16.46212 – 2009/01/03.40647), *rms*=0.402". Nominal orbit: epoch 2011 Aug. 27.0.

No impact solutions were found for (144898) VD17 in the next 100 year in the future. Similar solution, no possible impact, were detected by the JPL NASA and by the NEODyS.

5. Conclusion

To compute precisely the impact solutions of (99942) Apophis and (144898) 2004 VD17 it is necessary to include small effects like relativistic effects, close approaching asteroids, the Yarkovsky/YORP effect. The use of the software OrbFit is helpful in computing exact possible impacts of asteroids with the Earth. Thanks for the OrbFit Consortium. Also the free software Solex was useful in this work.

6. Acknowledgment

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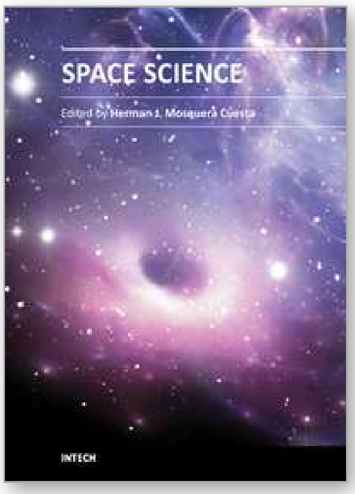

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The all-encompassing term Space Science was coined to describe all of the various fields of research in science: Physics and astronomy, aerospace engineering and spacecraft technologies, advanced computing and radio communication systems, that are concerned with the study of the Universe, and generally means either excluding the Earth or outside of the Earth's atmosphere. This special volume on Space Science was built throughout a scientifically rigorous selection process of each contributed chapter. Its structure drives the reader into a fascinating journey starting from the surface of our planet to reach a boundary where something lurks at the edge of the observable, light-emitting Universe, presenting four Sections running over a timely review on space exploration and the role being played by newcomer nations, an overview on Earth's early evolution during its long ancient ice age, a reanalysis of some aspects of satellites and planetary dynamics, to end up with intriguing discussions on recent advances in physics of cosmic microwave background radiation and cosmology.

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